PB82-143355

Spatial and Temporal Patterns of Eastern U.S. Haziness: A Summary

Washington Univ.
St. Louis, MO

Prepared for

Environmental Sciences Research Lab.
Research Triangle Park, NC

17 Feb 81

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completin

1. REPORT NO. EPA-600/J-81-485	2. Journal Article
3. F PB82-143355	
4. TITLE AND SUBTITLE SPATIAL AND TEMPORAL PATTERNS OF EASTERN U.S. HAZINESS: A Summary	5. REPORT DATE December 1981
	6. PERFORMING ORGANIZATION CODE 362016
7. AUTHOR(S) Rudolf B. Husar, Janet M. Holloway, David E. Patterson and William E. Wilson	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Center for Air Pollution Impact and Trend Analysis Box 1185 Washington University St. Louis, MO 63130	10. PROGRAM ELEMENT NO. CABN1D-02/0557 (FY-82)
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, N.C. 27711	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES
REFERENCE: Atmospheric Environment, 15(10/11):1919-1928, 1981.

16. ABSTRACT

One of the key features of the optical environment over the eastern U.S. is the frequent occurrence of regional haziness, particularly during the summer season. Four historical data bases were examined for estimation of the regional trend in haziness over the past 80 years: the surface visibility observations currently operated by the National Weather Service; historical visibility at Blue Hill, MA; the NOAA-WMO turbidity network measuring the extinction of solar radiation with a sun photometer since the 1960's; and a set of direct solar radiation monitoring stations operated since 1910.

In the 1970's the lowest visibility occurred in the region of the Ohio River. The strongest increase of haziness was noted in the states adjacent to the Smoky Mountains: the average visibility there has decreased from 24 to 10 km since 1948. That region also exhibits the highest turbidity (vertical optical depth of the aerosol). The spatial trends of coal consumption indicate a consistency with the spatial trends in haziness.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 12
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

EPA-600/J-81-485
Journal Article

Atmospheric Environment Vol. 15, No. 10/11, pp. 1919–1928, 1981
Printed in Great Britain

0004-6981/81/101919-10 $02.00/0

SPATIAL AND TEMPORAL PATTERN OF EASTERN U.S. HAZINESS: A SUMMARY*

RUDOLF B. HUSAR, JANET M. HOLLOWAY and DAVID E. PATTERSON
Center for Air Pollution Impact and Trend Analysis (CAPITA) Box 1185, Washington University, St. Louis, MO 63130, U.S.A.

and

WILLIAM E. WILSON
Environmental Protection Agency, Research Triangle Park, NC 27711, U.S.A.

(*First received* 10 *September* 1980 *and in final form* 17 *February* 1981)

Abstract—One of the key features of the optical environment over the eastern U.S. is the frequent occurrence of regional haziness, particularly during the summer season. Four historical data bases were examined for estimation of the regional trend in haziness over the past 80 years: the surface visibility observations currently operated by the National Weather Service, historical visibility at Blue Hill MA, the NOAA–WMO turbidity network measuring the extinction of solar radiation with a sun photometer since the 1960's, and a set of direct solar radiation monitoring stations operated since 1910.

In the 1970's the lowest visibility occurred in the region of the Ohio River. The strongest increase of haziness was noted in the states adjacent to the Smoky Mountains: the average visibility there has decreased from 24 to 10 km since 1948. That region also exhibits the highest turbidity (vertical optical depth of the aerosol). The spatial trends of coal consumption indicate a consistency with the spatial trends in haziness.

INTRODUCTION

The deterioration of the visual environment through the disappearance of the Milky Way, discoloration of the blue sky and reduction of visual range and clarity of nearby objects is the most evident manifestation of atmospheric aerosols.

Over the populous regions of the eastern U.S., visibility has "always" been restricted by haze, at least for as long as people remember. The names of the Blue Ridge and Smoky Mountains imply the existence of bluish haze in those regions well before industrialized times. In fact, it is reasonable to question whether the visibility has even been as good anywhere in the eastern U.S. as the current visibility in the southwest (Trijonis, 1979). The absolute and relative humidity as well as the vegetation density is higher in the east, both of which could be responsible for increased natural haze either from hygroscopic marine aerosols or from secondary aerosols originating from vegetation (e.g. Went, 1960). A possible way of resolving this question is by searching old records of atmospheric visibility with the aim of establishing the "pre-industrial" visibility and its perturbation with time by the various activities of man.

Over the past decades, a general increase in haziness over the NE quadrant of the U.S. and SE Canada has been noted by airline pilots, and there have been reports of declining summertime visual range in that region (Miller *et al.*, 1972; Munn, 1973; Inhaber, 1976; Vickers and Munn, 1977). Over ten years ago, Flowers *et al.* (1969) documented the spatial and seasonal pattern of atmospheric turbidity over the U.S. covering the period 1961–1966. They noted that over the eastern half of the U.S. the attenuation of direct solar radiation due to atmospheric aerosols was 2–3 times higher than over the arid and non-industrialized central and western states. Unfortunately, the existing literature contains no systematic evaluation of regional trends of haziness over the eastern half of the U.S.

This paper, therefore summarizes our recent studies on the spatial-temporal pattern of eastern U.S. haziness,† as reflected in reduction of the meteorological visual range, (Husar *et al.*, 1979; Husar and Holloway, 1981) changes in atmospheric turbidity at 0.5 μm wavelength (Husar, 1981a) and the variations in broadband direct solar radiation intensity (Husar, 1981b). Further details on these studies may be found in the above papers. A short description of the data bases used in this summary is given in the appendix.

* Paper presented at the Symposium on Plumes and Visibility: Measurements and Model Components, Grand Canyon, Arizona, U.S.A. 10–14 November 1980.

† Haze refers to the light scattering and absorbing aerosols in the atmosphere. It is analogous to pollutants such as SO_2, CO, etc. Haziness, or the degree of haze, is a measure of light scattering and absorption. It is analogous to the concentration of pollutants. The unit of haziness is light extinction cross section (m^2) per unit of air volume (m^3), b_{ext} (m^{-1}). In this context the term's usage *excludes* specific visual sensations such as blurring of distant objects.

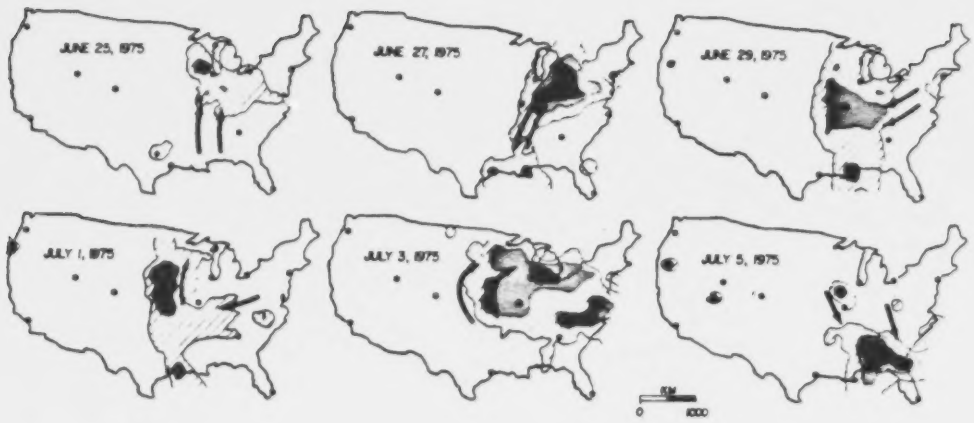

Fig. 1. Sequential contour maps of noon visibility for 25 June–5 July, 1975 illustrate the evolution and transport of a large scale hazy airmass. Contours correspond to visual range 6.5–10 km (light shade), 5–6.5 (medium shade), and < 5 km (black).

SPATIAL-TEMPORAL PATTERNS

The variability of haze can be expressed over at least four different spatial–temporal scales: diurnal-mesoscale (1 day, < 500 km); synoptic (1 week, approx. 2000 km), seasonal (1 year, global), and secular (> 10 years, global). In what follows, the eastern U.S. haziness is illustrated over these spatial–temporal scales using visual range, turbidity, and solar radiation data.

Diurnal–mesoscale

Haziness exhibits a diurnal pattern either due to variability of nearby emissions or, more likely, due to diurnally varying relative humidity; thus the most intense haziness typically occurs in the humid early morning hours. Visual range as a measure of "dry" haze is most meaningful around local noon when the relative humidity is normally < 70%. The scale of atmospheric transport is on the order of 500 km day^{-1}. The details of the diurnal-mesoscale are beyond the scope of this summary.

Synoptic

The synoptic temporal scale refers to the passage of large scale weather systems over a region, each having a duration on the order of one week.

The pattern of haziness over a one week period is determined by the synoptic wind field of large scale weather systems, e.g. high pressure regions (anticyclones), fronts, etc. The synoptic scale accumulation of "hazy blobs" over industrialized source regions and the subsequent haze transport to receptor regions has been receiving much recent attention (e.g. Hall *et al.*, 1973; Husar *et al.*, 1976; and Wolff *et al.*, 1977). An illustration of the evolution and transport of such synoptic scale haze episodes is given in Fig. 1.

The daily time series for 2 p.m. extinction coefficient, b_{ext}, is illustrated for three characteristic years at Blue Hill, MA (Fig. 2) and for two years at Charlotte, NC (Fig. 3). As in all other calculations, all days were included, irrespective of the weather conditions, e.g. rain, fog, snow, etc. At Blue Hill, the winter (quarter 1) haziness is generally characterized by frequent but short term events of visibility obstruction, lasting only a few days at a time. In the summer (quarter 3) such events lasted over ten days in some instances (see 1906). The increased haziness throughout the year in 1906 and 1958 is evident when compared to the cleaner year of 1932.

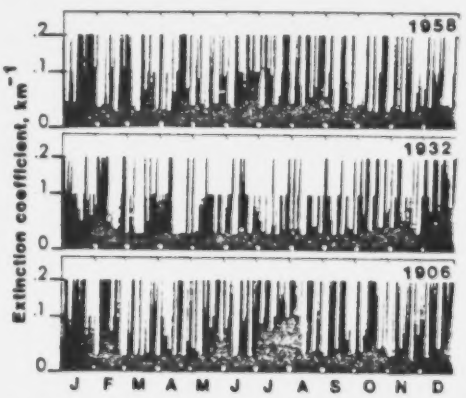

Fig. 2. The daily variation of b_{ext} during three characteristic years at Blue Hill, MA. Note the low frequency of high b_{ext} days in 1932.

The records for Charlotte, NC for 1952 and 1972 (Fig. 3) also demonstrate the strong day to day variability of the haziness, b_{ext}. Hence, the haziness (b_{ext}) is considered to be "episodic" with the "episodes" occurring in random time intervals.

Seasonal

A general pattern of haziness emerges when the highly variable daily values are averaged over a longer

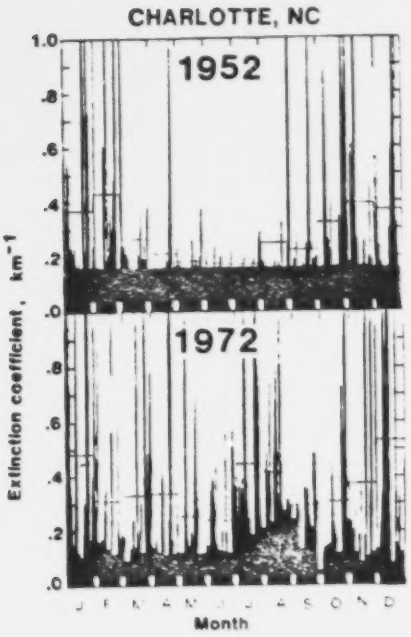

Fig. 3. Pattern of day to day extinction coefficient for Charlotte, NC in 1952 and 1972. The summer of 1952 was essentially free from haziness > 0.16 km^{-1} (visual range < 24 km). By 1972, over most of the summer the haziness was > 0.16 km^{-1}.

period. Essentially all of the parameters influencing haziness, including emissions, transport, transformation and removal, as well as the properties of haze aerosol, exhibit strong seasonally periodic patterns. It is thus beneficial to average the pattern of haze parameters seasonally rather than as an annual average.

The spatially averaged patterns of haze optical depth at 0.5 μm (turbidity), τ_H, are depicted in Figs 4a, b and c. In the cold season (Fig. 4a), October–March of 1961–66, the highest optical depths were recorded in the major metropolitan areas, New York (0.33), Chicago (0.39), and St. Louis (0.28). However, $\tau_H > 0.2$ values prevailed over 17 eastern U.S. sites, occupying a belt that stretched from Texas to the industrialized north-eastern U.S. By 1972–75 the high turbidities in the industrialized cities had been reduced, but there is evidence of an increase in the east-central states centered about Tennessee.

The warm season (April–September) turbidities (Fig. 4b) in 1961–66 were also higher in major industrial–urban areas than in neighboring rural areas, e.g., Rockefeller Plaza–Upton, New York; Cincinnati GSEF–Cincinnati. However, even in the non-urban eastern U.S. sites, the warm season values were $\tau_H > 0.3$. Possible exceptions are New England, Florida, and Michigan where there were no stations. In 1961–66, optical depths in excess of 0.5 were recorded only at Rockefeller Plaza, New York, and Baltimore. By 1972–75, multi-state areas of the southeastern U.S. were covered by a haze blanket with an average warm

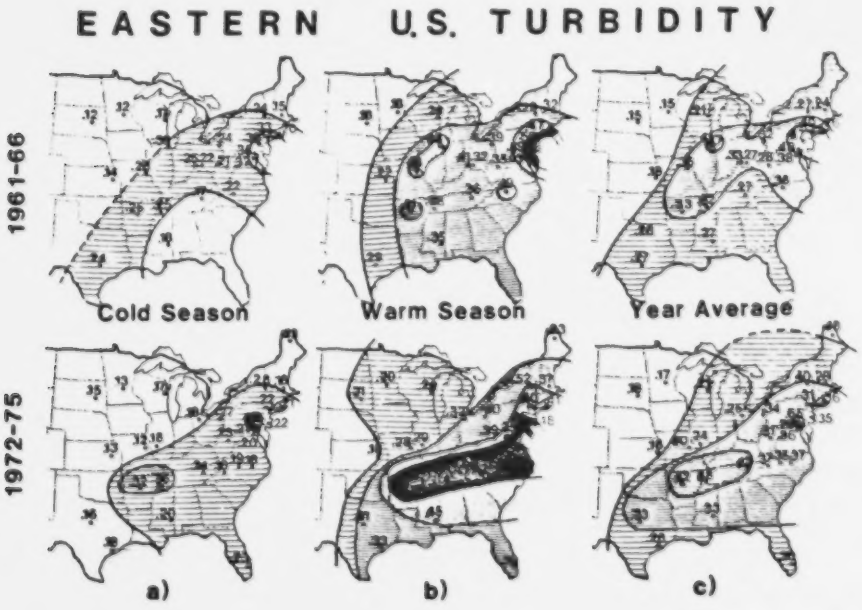

Fig. 4. Spatial distribution of haze vertical optical depth at 0.5 μm in 1961–66 (top row) and 1972–75 (bottom row) from 26 sites. (a) Cold season, October–March, (b) Warm season, April–September and (c) Yearly average.

season optical depth $\tau_H > 0.5$. The region evidently extended from Arkansas through Tennessee to the East Coast. The increase of the warm season turbidity in the south-central states and the τ_H reduction in some major metropolitan areas constitutes one of the main findings of this trend research.

The annual average turbidity depicted in Fig. 4c indicates that in 1961–66 high τ_H values (> 0.3) were confined to the populous and industrialized regions of the northeast and midwest, but $\tau_H > 0.2$ covered the entire region east of the Mississippi River. By 1972–75, $\tau_H > 0.3$ values shifted toward the south-central states centered around Tennessee, where the annual averages exceeded 0.4.

In summary, the territory in and around the Smoky Mountains exhibits the most pronounced change in haziness; the Smoky Mountains, to a greater extent than the rest of the eastern U.S., were more "turbid" in the 1970's than in the 1960's. This is evident from both the visual range (next section) and optical depth measurements.

The average monthly pattern of the haze optical depth (turbidity), τ_H, at 26 eastern U.S. sites (shown in Fig. 4) and the standard deviation of monthly average values among the sites is depicted in Fig. 5. The eastern U.S. average τ_H ranges from 0.2 in December–February to $\tau_H \approx 0.5$ in June–August. In the pristine central and western states, all τ_H values are below 0.2.

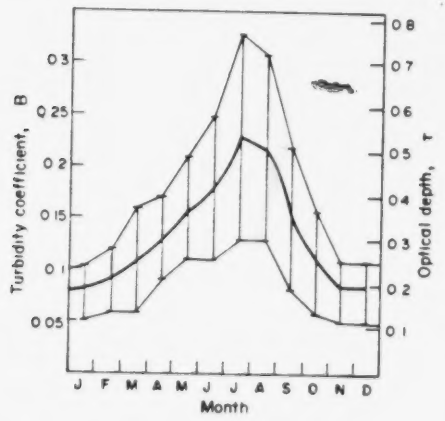

Fig. 5. Seasonal pattern of the monthly average haze optical depth, τ_H (or turbidity coefficient $B = 2.3\tau_H$), at 26 eastern U.S. sites, 1972–1975.

The seasonal patterns of haziness deduced from routine visual range observations are further discussed in the next section dealing with secular trends. Examination of numerous similar seasonal patterns of extinction coefficient, turbidity and direct solar radiation loss all indicate that in the 1970's the eastern U.S. summer haziness exceeded the winter values. Historical U.S. visibility data (next section) indicate, however, that before the 1950's the reverse was true.

Secular trends

"Secular trends" of meteorological parameters refers to systematic changes over periods greater than 10 years. Secular trends of haziness (light extinction by aerosols) may be caused by drifts in climatological variables such as temperature, relative humidity, precipitation, etc. or by the changes in the concentration of the scattering and absorbing aerosols resulting from shifts in their emission pattern.

The spatial distributions of five-year seasonally averaged extinction coefficients from routine visual range observations (Fig. 6) show the drastic increases of quarter 3 extinction coefficients in the Carolinas, Ohio River Valley, and Tennessee-Kentucky area. In the summers of 1948–1952, a region centered around Atlanta, Georgia, had visibility greater than 24 km, which declined to less than 13 km by the 1970's. The spatial trend of winter (quarter 1) visibility shows improvements in the "N. E. Megalopolis" region and some worsening in the "Sunbelt" region. Both spring and fall quarters exhibit a moderate but detectable increase of b_{ext} over the entire eastern U.S.

The trend of mean extinction coefficient for 70 eastern U.S. stations over 27 years (1948–1974) shows appreciable station-to-station variability. However, visual inspection and sorting has revealed that neighboring stations exhibit consistent secular trends within a given region. The resulting region boundaries and the location of the trend stations are shown in Fig. 7(a).

Examples of the secular trends of extinction coefficient calculated from visibility observations for the "New England" and "Smoky Mountain" regions are shown in Fig. 7. The mean b_{ext} for each season is depicted as a solid line; the shaded area represents the standard deviation of station means within that region.

"New England" extinction coefficient declined in winter and increased in spring and summer, while fall average b_{ext} remained essentially unchanged. The "Smoky Mountain" region displays a very strong increase in summer average b_{ext} from about 0.16 to $0.4\,km^{-1}$, corresponding to a characteristic visibility decline from 24 to 10 km. Evidently the Smoky Mountains have become appreciably "smokier" over the past 20 summers.

The 70-year record of extinction coefficient at Blue Hill, MA (Fig. 8) for the four seasons and two observation hours shows a remarkable double peak pattern: the median extinction coefficient (haziness) was low in the 1890's, rose to a higher level in the 1900–1920 period, declined around 1930, increased again in the 1940's, and decreased until the end of the record in 1958. The strong decline of median b_{ext} to pre-1890 levels during the Great Depression years is most evident in the 8 a.m. observations. The morning median visibility improved from about 20 km around 1910–1920 to 50 km in 1930.

The 2 p.m. median b_{ext} values have exhibited a less dramatic drop around 1930 from 0.1 to 0.07 or a visibility improvement from 35 to 55 km median visual range. We should note, however, that the absolute

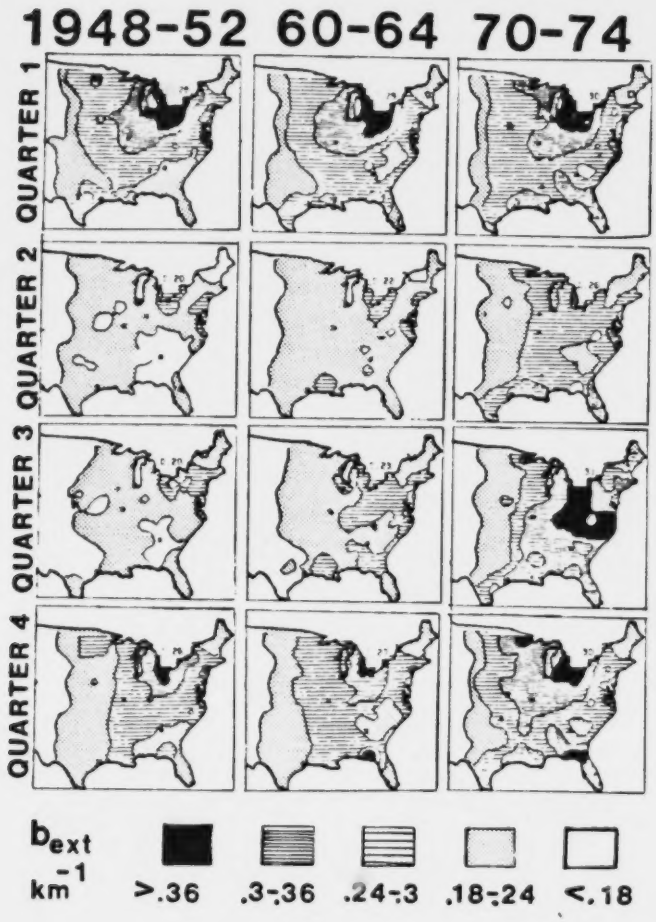

Fig. 6. Contour maps of 5-y average extinction coefficients by season, about 1950, 1962 and 1972. The eastern U.S. average extinction coefficient is indicated above each map.

values of b_{ext} are rather low for eastern U.S. conditions, only a factor of 3 to 5 larger than the light scattering by aerosol free air (Rayleigh scattering $\approx 0.02\,km^{-1}$).

The quarterly historical trend of the broadband haze optical depth, τ, as calculated from solar radiation loss data at Madison, Wisconsin since 1916 is shown in Fig. 9. The τ values at relative airmass $m_r = 2$ (solid lines) and $m_r = 3$ (dashed lines) show appreciable year-to-year variability. It is evident, however, that a noticeable peak in the haze optical depth, τ, occurred in the 1940's. The cause of the sudden rise of τ in 1978 is not clear, but at this time we would not attribute major significance to the one year anomaly.

In summary, the secular trend of horizontal extinction coefficient and solar radiation loss due to aerosols (at 0.5 μm and averaged over the entire spectrum) shows a dynamic pattern over the past 90 years, characterized by a sharp drop around 1930 and a strong peak during the 1940's. Another increase in haziness occurred from 1960 to the mid-1970's.

POSSIBLE CAUSES OF EASTERN U.S. HAZINESS

The above examination of the historical data bases for eastern U.S. haziness was focused exclusively on its spatial and temporal pattern, i.e. on the haze *per se*. Neither the haze properties (physical or chemical) nor its specific sources were addressed since the goals of this quest were to explore gross relationships between "industrialization" and haziness. The sector of industrialization pertinent in this context is the amount of fossil fuel combustion. It therefore appeared meaningful to compare the secular trends of haziness to the trends of fossil fuel combustion since 1850.

Fig. 10 depicts the national U.S. consumption of fire wood, crude oil, anthracite and bituminous coal, the

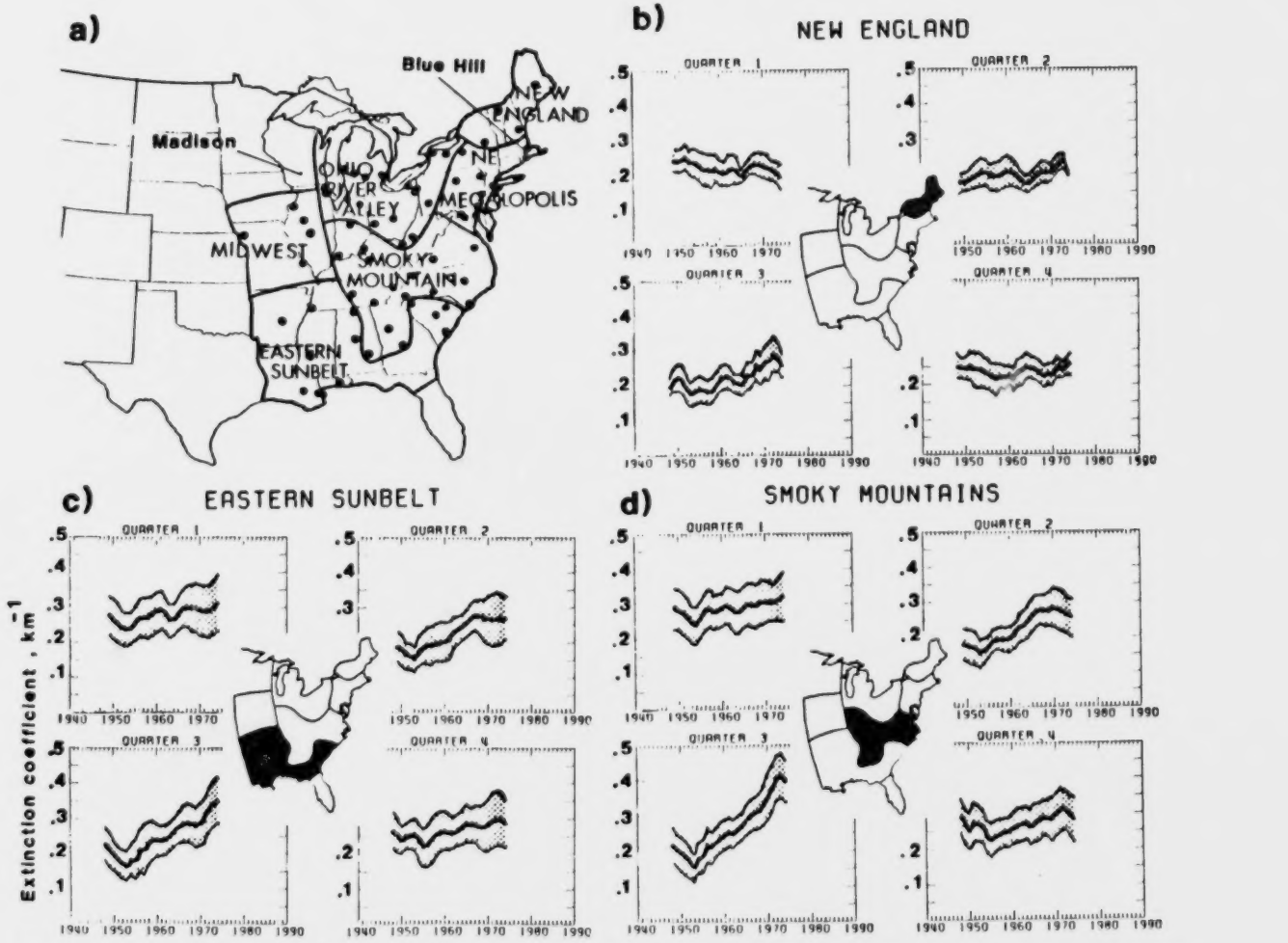

Fig. 7(a). Location of the 70 eastern U.S. meteorological stations and regional boundaries; Blue Hill, MA; and Madison, WI; (b-d) Trends of extinction coefficient, by season for the "New England", "Eastern Sunbelt" and "Smoky Mountain" regions.

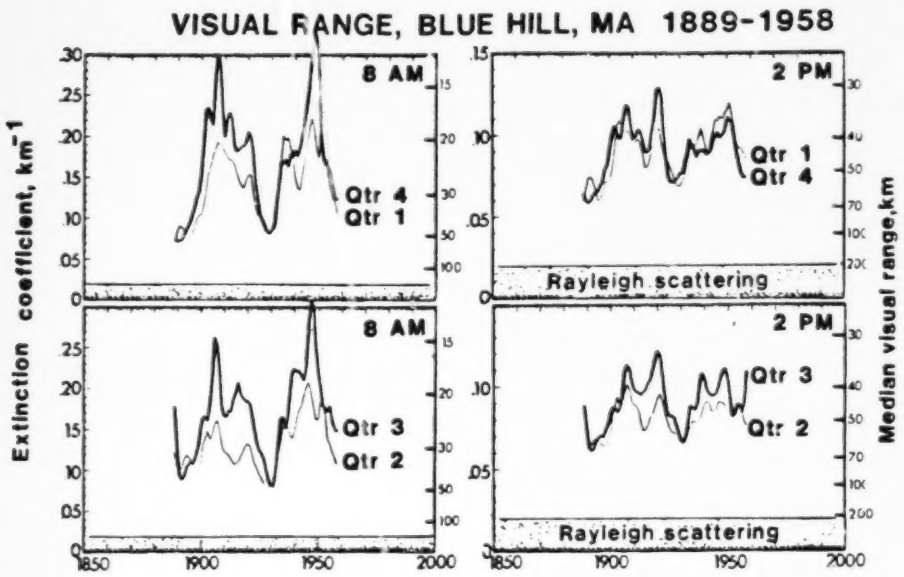

Fig. 8. The median b_{ext} at Blue Hill, MA for each quarter shows two peaks, the first in the 1900–20 period, second between 1935 and 1955.

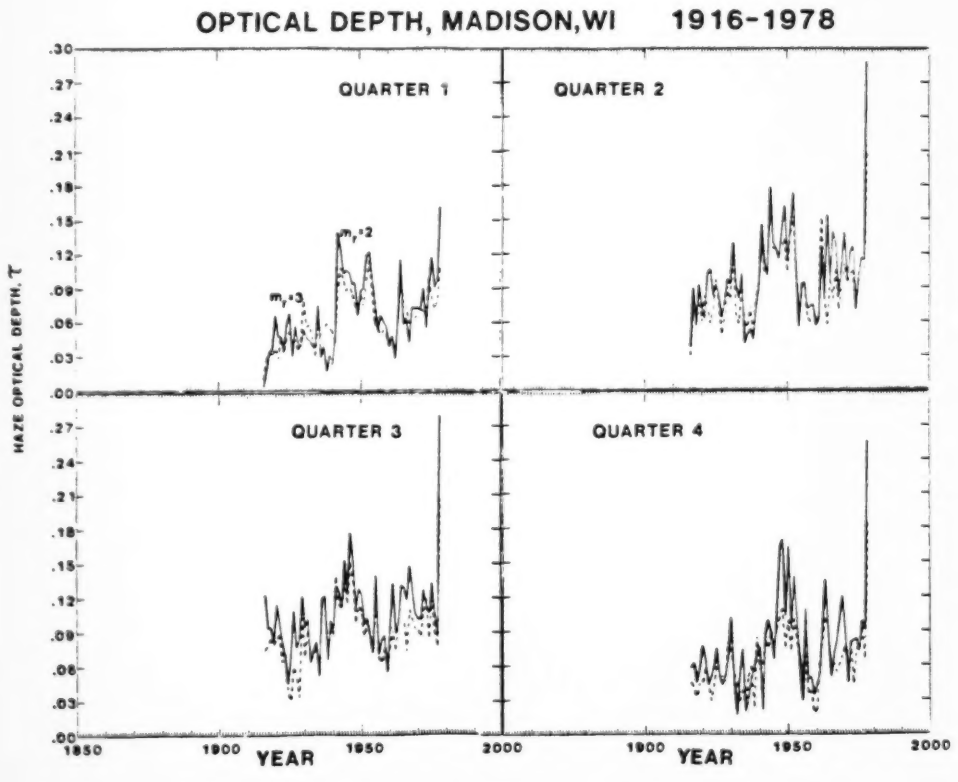

Fig. 9. Secular trends for Madison, WI of quarterly broadband aerosol optical depth, τ, calculated from the attenuation of the entire solar spectrum.

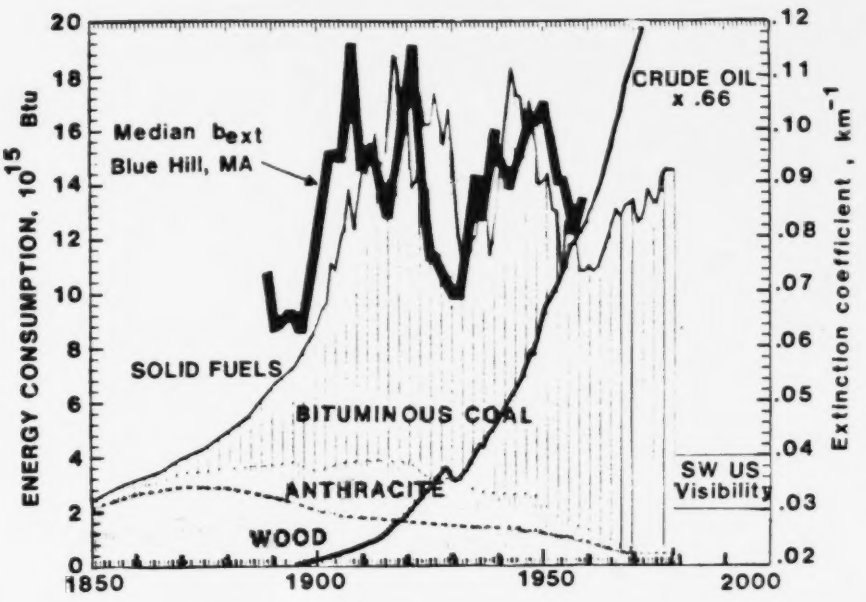

Fig. 10. Secular trends of firewood, anthracite and bituminous coal and crude oil since 1850 (Data from U.S. Bureau of Census) compared to the annual median extinction coefficient at Blue Hill (1889–1958).

"dirty" fuels, since 1850. As a guide to the eye the three year moving average of the median b_{ext} at Blue Hill averaged over the four quarters of each year is also entered.

A key feature of the fuel use—Blue Hill haze comparison (Fig. 10) is that before 1958 the secular trends resemble the pattern of coal consumption more than the use of crude oil and all its products. We are also aware that since 1958 50–60% of the light scattering over the eastern U.S. is attributed to sulfur compounds and the associated water (U.S. EPA, 1979). Furthermore, over 75% of the eastern U.S. sulfur emissions are from coal combustion (NAS, 1978). Hence, coal consumption is considered the most significant direct cause of eastern U.S. haziness in the 1970's.

The secular trend of regional coal use is indicated in Fig. 11. In the "Ohio River" region (Indiana, Michigan, Ohio, Pennsylvania) the coal consumption was high in the late 50's and early 60's and has further increased since 1960. "New England" coal consumption has declined since about 1965, reflecting the fuel shift from coal to oil. This was also the case for the "N.E. Megalopolis" states of New York, Maryland and Virginia. The strongest increase in coal consumption was recorded for the states of Kentucky, West Virginia, North and South Carolina and Tennessee, defined previously as the "Smoky Mountain" region. In that region, essentially all of the growth was due to electric utility coal (dark shading). Increases in haziness were most pronounced in the east central U.S., which is consistent with (but not necessarily caused by) the strong rise in coal demand.

The superposition of "dirty" fuel use and selected haze parameters (Fig. 10) also leads to a disappointing conclusion: our search for "pre-industrial" levels of haziness has not been successful. By 1890, the consumption of wood, anthracite and bituminous coal was almost half (6×10^5 btu) of the solid fuel use since 1900 (approx. 15×10^{15} btu). Records indicate that as early as 188[illegible]-made smoke was observed as haze on the horizon and obscured the visibility of distant mountains at Blue Hill. We must also bring to the reader's attention the peculiar drop in haziness around 1925, almost five years *before* the Great Depression.

According to Trijonis (1979), the current median visibility at nonurban sites in the southwest is between 130 and 100 km, corresponding to median extinction values of 0.03 and 0.04 km^{-1} as depicted in Fig. 10. The specific question we are asking is: suppose that all of the fuel combustion is stopped at once, would the b_{ext}, say at Blue Hill, be reduced to 0.03–0.04 km^{-1}? It is very tempting to seek a "correlation" between the haziness and the fuel use, estimate "confidence limits" and to extrapolate to "zero fuel use", i.e. to the natural haziness. We feel however that such a delicate act should be left to the reader and in the realm of intuition rather than obscured by statistics or speculation.

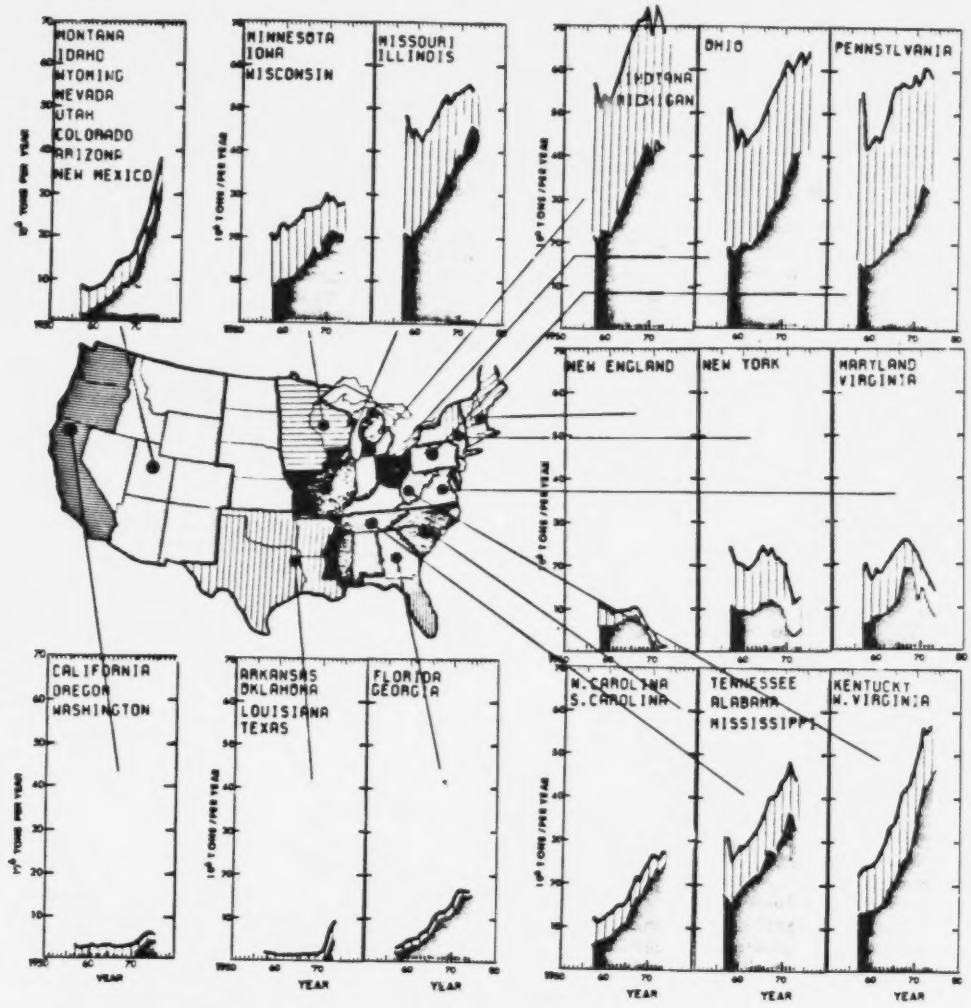

Fig. 11. U.S. annual coal consumption trends.

Acknowledgement—This work was supported by EPA Grant No. CR80660602.

REFERENCES

Flowers E. C., McCormick R. A. and Kurfis K. R. (1969) Atmospheric turbidity over the United States, 1961–1966. *J. appl. Met.* **8**, 955–962.

Flowers E. C., McCormick R. A., Kurfis K. R. and Bilton T. H. (1974) WMO Special Env. Report, No. 3, WMO, No. 368.

Hall F. P. Jr., Duchon C. E., Lee L. G. and Hagan R. R. (1973) Long-range transport of air pollution: A case study, August 1970. *Mon. Weath. Rev.* **101**, 404.

Hand T. F. (1937) Review of United States Weather Bureau solar radiation investigations. *Mon. Weath. Rev.* **65**, 415–441.

Husar R. B., Gillani N. V., Husar J. D., Paley C. C. and Turcu P. N. (1976). Long-range transport of pollutants observed through visibility contour maps, weather maps and trajectory analysis. Preprints, Third Symposium on Turbulence, Diffusion, and Air Pollution, American Meteorological Society, Boston, pp. 344–347.

Husar R. B., Patterson D. E., Holloway J. M., Wilson W. E., Jr. and Ellestad T. G. (1979) Trends of eastern U.S. haziness since 1948. In Preprints. Fourth Symposium on Turbulence, Diffusion, and Air Pollution, American Meteorological Society, Boston, pp. 249–256.

Husar R. B. (1981a) Atmospheric turbidity over the United States, 1961–1975. Submitted for publication.

Husar R. B. (1981b) Trend of direct solar radiation intensity at Madison, WI, 1916–1977. Submitted for publication.

Husar R. B. and Holloway J. M. (1981) Visibility trend at Blue Hill, MA, since 1889. *Bull. Am. met. Soc.* (in press.)

Inhaber, H. (1976) Changes in Canadian national visibility. *Nature* **260**, 129–130.

McCormick R. A. and Baulch D. (1962) The variation with height of the dust loading over a city as determined from the atmospheric turbidity. *J. Air Pollut. Control Ass.* **12**, 492–496.

Miller M. E., Canfield N. L., Ritter T. A. and Weaver C. R. (1972) Visibility changes in Ohio, Kentucky and Tennessee from 1962 to 1969. *Mon. Weath. Rev.* **100**, 67–71.

Munn R. E. (1973) Secular increases in haziness in the Atlantic provinces. *Atmosphere* **11**, 156–161.

National Academy of Sciences (1978) Sulfur Oxides. Committee on Sulfur Oxides, Board on Toxicology and Environmental Health Hazards, Assembly of Life Sciences, National Research Council, National Academy of Sciences, Washington, D.C.

Peterson J. T. and Flowers E. C. (1977) Interactions between air pollution and solar radiation. *Sol. Energy* **19**, 23–32.

Trijonis J. (1979) Visibility in the Southwest—an exploration of the historical data base. *Atmos. Envir.* **13**, 833–843.

U.S. Bureau of the Census (1975) *Historical Statistics of the United States, Colonial Times to* 1970, Washington, D.C., 587–588.

U.S. Environmental Protection Agency (1979) Protecting Visibility. An EPA Report to Congress. EPA-450/5-79-008. Research Triangle Park, NC.

Vickers G. G. and Munn R. E. (1977) A Canadian haze climatology. *Climate Change* **1**, 97–103.

Volz F. (1959) Photometer mit selen-photoelement zur spectralen messung der sonnenstrahlung und zur bestimmung der wellenlengenabhangigbeit der dunsttrubung. *Arch. Met. Geophys. Meoklim.* (*B* 10) **100**, 131.

Went F. W. (1960) Organic matter in the atmosphere, and its possible relation to petroleum formation. *Proc. natn. Acad. Sci. U.S.A.* **46**, 212–221.

Wolff G. T., Lioy P. J., Wight G. D., Meyers R. E. and Cederwall R. T. (1977) An investigation of long-range transport of ozone across the midwestern and eastern United States. *Atmos. Envir.* **11**, 797–802.

APPENDIX: DATA BASES

Visual range

The visual range is the maximum distance at which an observer can discern the outline of a black object against the horizon sky. Haziness, measured by the extinction coefficient, b_{ext} is proportional to the inverse of the visual range, $b_{ext} = K/(\text{visual range})$, where K is the Koschmieder constant (3.9 if the observer's contrast threshold is 0.02). The extinction coefficient is proportional to the concentration of light scattering and absorbing aerosols and gases. Values of ground level visual range have been recorded every hour at several hundred meteorological stations within the U.S. Historical data since 1948 from 70 such sites were used in the U.S. visibility trend study.

A much older data base on visual range is available for the Blue Hill Observatory in Massachusetts (Husar and Holloway, 1981). Starting in 1889 the standard meteorological measurements were augmented by a simple estimation of visual range: the observation of three distant mountain tops in the W-NW direction at distances of 32, 72 and 107 km from the observatory. The observers recorded twice daily (8 a.m. and 2 p.m.) the number of visible mountain tops (0, 1, 2 or 3). This simple and apparently reliable mode of observation and recording was maintained until 1958 when these observations were discontinued. For the Blue Hill data, the b_{ext} was set at $0.036\,km^{-1}$ if all mountains were visible, and at 0.054 and $0.12\,km^{-1}$ for 2 and 1 visible mountains respectively. The value of b_{ext} when none of the mountains were discernible was chosen *arbitrarily* to be $0.2\,km^{-1}$. Owing to the coarse spatial resolution of the visual targets, the above values are an overestimation of the daily b_{ext} values.

The median extinction coefficient (which is also the median visual range) was estimated from cumulative log-probability plots for each season and hour of observation.

Haze optical depth, τ_H, at 0.5 μm

"Turbidity" is a measure of vertical atmospheric transparency to shortwave radiation. Normally it refers to the atmospheric attenuation of incoming solar radiation, but it also covers the extinction of moon or stellar radiation. Since the 1960's atmospheric turbidity has also been an important factor in determining the transmission of reflected or emitted radiation reaching remote sensing satellites.

The U.S. turbidity monitoring network, initiated in 1960–61, consists of 25–35 stations utilizing sun photometers designed by Volz (1959) or similar devices constructed by EPA/NOAA (Flowers *et al.*, 1974) which measure the direct solar radiation intensity in a narrow band near $\lambda = 0.5\,\mu m$. The EPA/NOAA sun photometer also measures the solar radiation intensity at $\lambda = 0.38\,\mu m$. However in this analysis only the $0.5\,\mu m$ channel will be used. The characteristics, calibration and use of the simple photometers have been discussed by Volz (1959), McCormick and Baulch (1962), Flowers *et al.* (1969), and Peterson and Flowers (1977), among others.

In a narrow wavelength range ($\lambda \approx 0.5\,\mu m$), Beer's law is applicable for the calculation of extinction of extraterrestrial solar radiation intensity, I_0, as it passes through the atmosphere:

$$\frac{I}{I_0} = e^{-\left(\tau_R \frac{P}{P_0} + \tau_0 + \tau_H\right) m_r}$$

where the optical depth of the Rayleigh atmosphere at $\lambda = 0.5\,\mu m$ and relative airmass $m_r < 3$ is $\tau_R = 0.146$ (P/P_0 is a correction factor to τ_R for the deviation of the station pressure P from the sea level pressure P_0). Ozone optical depth is $\tau_0 = 0.009$ (McCormick and Baulch, 1962).

The haze optical depth, τ_H, is calculated from the measured solar radiation intensity, I, and known values of I_0, τ_R, τ_0 and m_r. In what follows, the haze optical depth at $0.5\,\mu m$ is expressed in natural $\log_e$ units (τ_H) or as "turbidity coefficient" $B = 2.3\,\tau_H$.

Broadband aerosol optical depth

The measured value of the direct solar radiation intensity, when compared to the solar constant, yields the total atmospheric transparency for direct solar radiation. After accounting for Rayleigh scattering, ozone and water absorption, the remaining optical depth is attributed to haze optical depth pertinent to the entire solar spectrum (e.g. Husar, 1981b).

At Madison, a Marvin pyrheliometer was used to monitor the direct solar radiation intensity starting in 1916 (Hand, 1937). The detector is essentially a resistance thermometer attached to a blackened, thermally absorbing and well conducting silver disc located on the bottom of a tube facing the sun. The tube is periodically opened to direct solar radiation and the resulting rise in the silver disc temperature is calibrated against the solar flux in the 0.3–2.5 μm wavelength range. Data are reported only when the sun is unobscured by clouds.

The raw data of the over 60 year record consist of direct solar radiation intensity records at several solar zenith distances between 60° (relative air mass $m_r = 2$) and 79.8 ($m_r = 5.5$).